COMPACT NEUTRON SOURCES FOR PURE AND APPLIED SCIENCE

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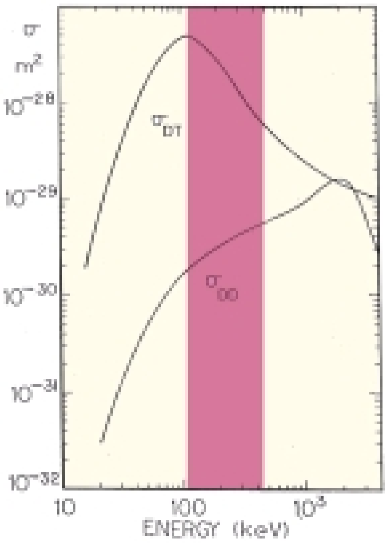
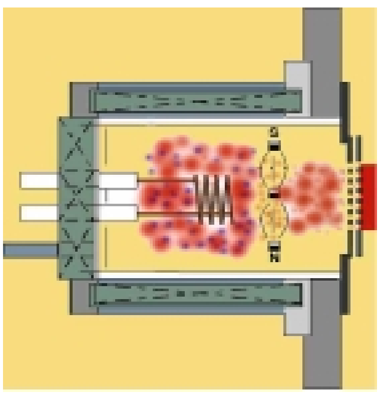
The Accelerator and Fusion Research Division of the Lawrence Berkeley National Laboratory has been developing a new generation of neutron sources for university scale research laboratories, for clinical use and for portable field applications. While neutron tubes are not a substitute for fission reactors and accelerator driven spallation sources for the copious production of neutrons for the most demanding users, they can meet the operational needs (Table 1) of a wide range of researchers and clinicians especially in the University and small laboratory environment.

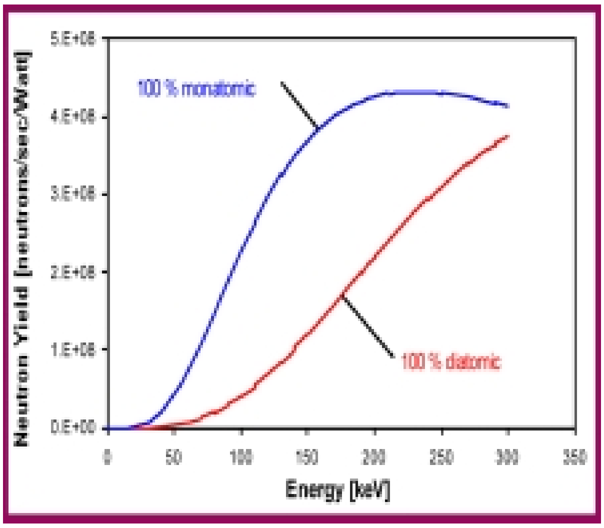


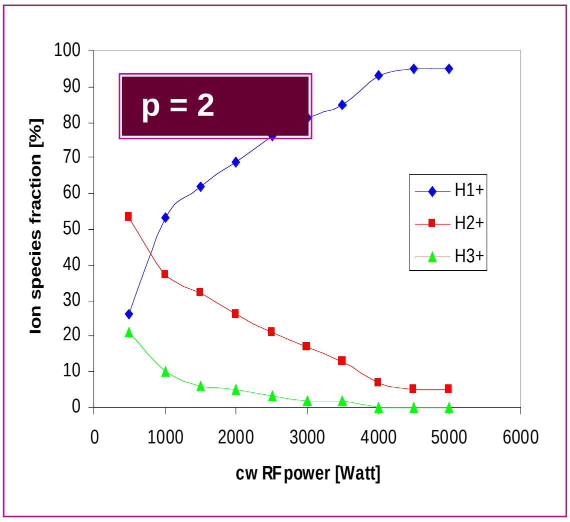
The new generation of compact neutron tubes being developed by the Berkeley Lab are based on D-D and D-T fusion reactions. The reaction cross sections shown in the figure suggests that the ideal neutron tube is a deuteron or triton accelerator operating at 100-200 keV.

The compact accelerator begins with a plasma source of deuterons (or mixed Deuterium-Tritium). The deuteron beam is extracted from the plasma volume through high-voltage electrodes to impact a deuterated or tritiated target plate. Neutrons are emitted from the target plate and pass through a moderator to produce a neutron beam of the desired energy. The heart of the tube is a sealed ion source. The source consists of a container lined with permanent magnets which contain a plasma that is generated by a radio frequency discharge from an rf-antenna. The figure shows the beam container, the antenna, the gas inlets and beam extraction electrodes.

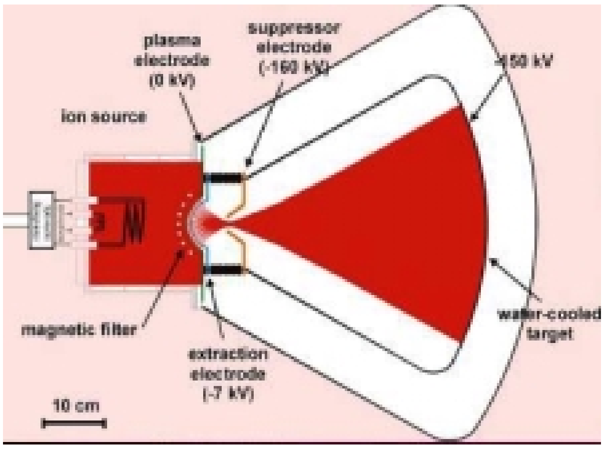


An important part of the source is a magnetic beam filter which assures that only the desired species of ion (correct atomic or molecular state) is extracted. In our case we



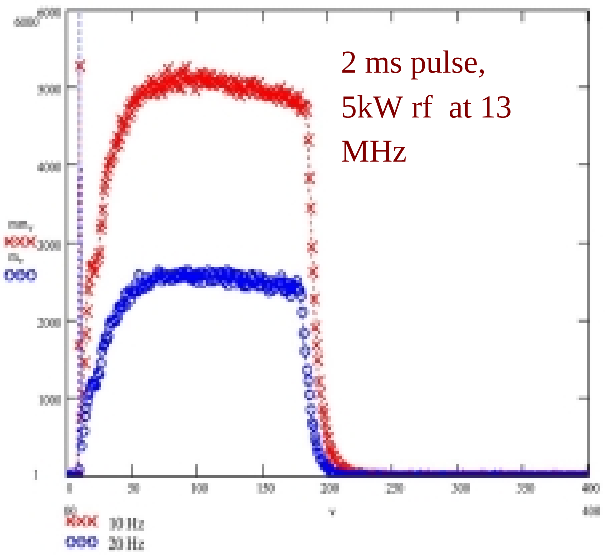


extract atomic hydrogen ions; the molecular ions which are extracted have only an energy per nucleon which results in a much lower fusion cross-section and therefore lower neutron yield per watt. The measured yield for deutrons incident on a tritium-implanted, titaniam plated copper target is as shown. Ones sees that the optimum voltage is ~170 keV for an atomic tritium beam. (Sandia data). Further control of the beam species is also determined by the amount of rf-power fed into the discharge. Our measurements of this dependence suggest that a few kW of ~ 10 MHz rf-power yields nearly all monatomic hydrogen in the beam.

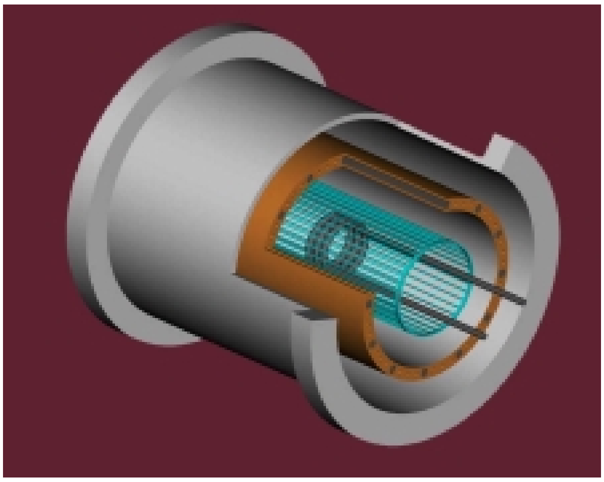


The first LBNL realization of the compact neutron generator is a sealed tube design that employs cross over beam optics to eliminate the erosion of the high voltage suppressor electrode. This design feature simultaneously improves the uniformity of the beam incident on the target.

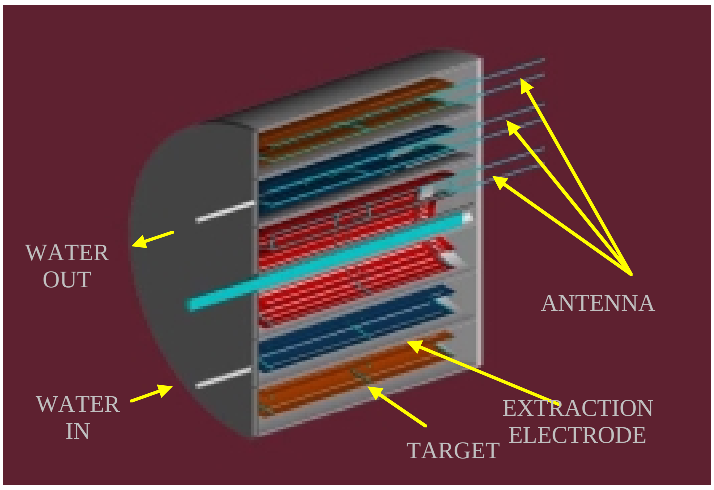
Unlike earlier versions of "neutron tubes" (such as the Livermore Rotating Target Neutron Source) which used a target made of titanium chemically bonded with tritium, the Berkeley tube uses a thin titanium layer bonded to a copper substrate with cooling channels. The tritium or deuterium is physically loaded onto the surface of the target by the beam. Thus the hydrogen cannot be depleted from the target as it is continually replenished by the beam. The target lifetime is limited by sputtering; the lifetime can be evaluated by using H ions so that no prompt radiation or activation is produced in the test components.



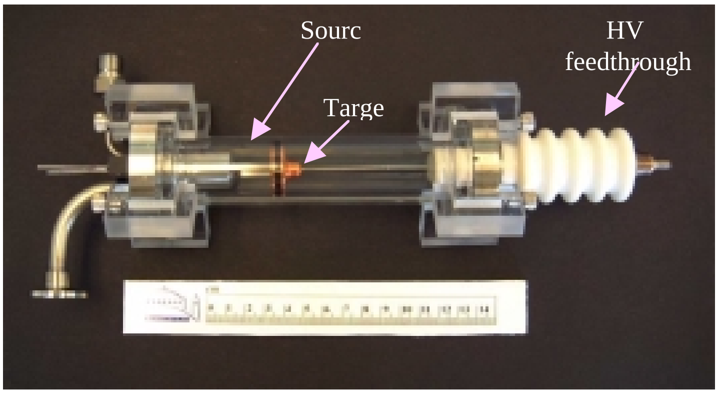
Initial tests of neutron production have been conducted at low duty factor to minimize the shielding required at our experimental facility. The present shield is composed of 3 cm of borated polyethylene surrounded by 5 mm of lead sheet held in place between 1 cm plywood sheets. Tests of the tube operating at 150 keV demonstrate a remarkable pulse-to-pulse reproducibility especially in the sharp fall time of the 2 ms neutron pulse. The data taken by a Los Alamos group employ cadmium, shielded detectors to measure the non-thermal neutron flux.



The next series of neutron tubes employs a coaxial geometry to increase the neutron yield per unit volume by increasing the available target area. In a tube with dimensions - length = 26cm, diameter = 28cm and weight = 40lb - operating at 80 keV and 1 A peak current, we expect an output of ~ 1.2 x 10^{12} n/s for D-D neutrons and ~ 3.5 x 10^{14} n/s for D-T neutrons at a duty factor of 10%. The neutron yield per watt could be tripled by raising the tube voltage to 170 keV at the cost of an increase in power supply cost per watt.

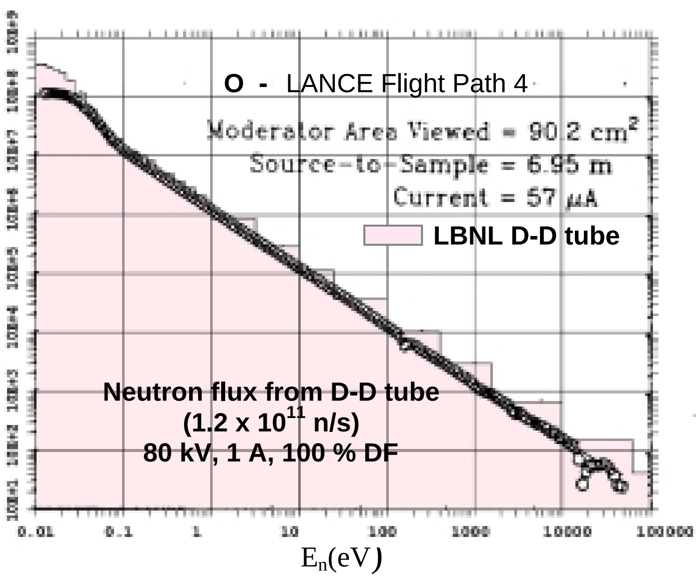


The limiting factor in tube performance is the power density on the target which we have set conservatively at ~650 W/cm^2. Tubes with as much as ten times higher average flux can be made by nesting the concentric targets and plasma regions as shown in the illustration. That design would yield a neutron output of ~ 1.6 x 10^{13} n/s for a D-D tube and as much as ~ 4.5 x 10^{15} n/s for an 80 keV D-T neutron tube. Here again another factor of three can be obtained by raising the tube voltage to 170 keV.

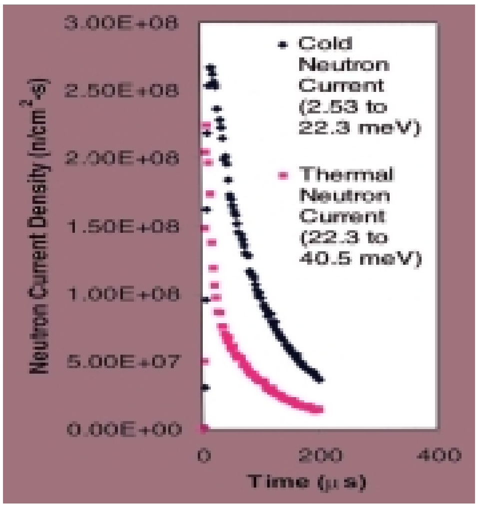


Tube geometry may be set by considerations other than maximum flux per unit volume. For example, for neutron radiography the geometry can be configured to yield a point source of neutrons. For applications such as down-hole well logging the tube must fit within a standard bore hole. For this purpose we have designed a 2 " (o.d.) tube. This small tube is also ideal for moderator design studies and for pedagogic purposes in training nuclear engineering students about experimental neutronics on any of the many university campuses without a research reactor.

The utility of neutron tubes for research comes from the fact that the initial neutron energy is low unlike the case of accelerator-driven spallation sources using high energy protons on a high Z target. Importantly the neutron production is not accompanied by a powerful burst of gamma rays. This fact means that both the moderator and the shielding can be much thinner than those surrounding a spallation target which produces copious neutrons with energies well in excess of 100 MeV (actually up to the full beam energy). We can compare the output of a small (10 cm long, 5 cm diameter), 80 kW D-D tube surrounded by 4 cm of liquid methane moderator and 10 cm of concrete shielding. The spectrum of the neutron flux in neutron/(cm^2-s-eV) is shown as the shaded histogram in the figure. For comparison the circles show the measured neutron flux v. neutron energy (Ref: Paul E. Koehler, Nuclear Instruments & Methods A292, 541 (1990)) at LANSCE operating at a beam power of ~ 50 kW. One sees that due to the considerable distance (7 m) of the instrument from the neutron source, the flux of the high energy spallation source is nearly identical to the performance of the compact neutron tube. The overall electrical efficiency

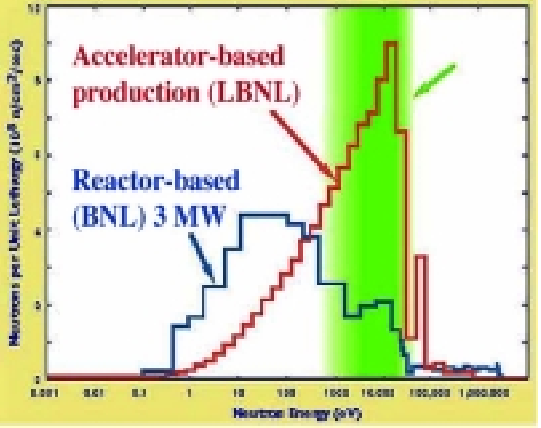


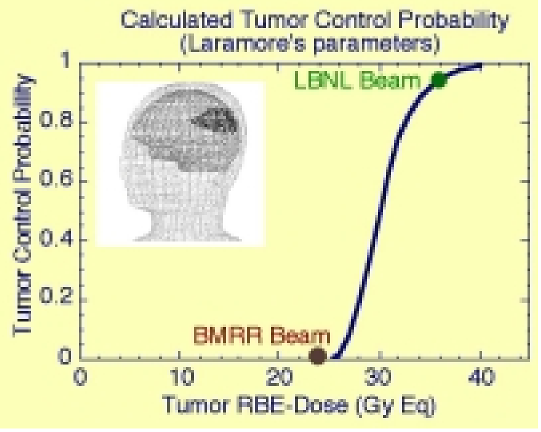
of a high power ~1 GeV proton accelerator is in range of 1 -10%, while the electrical efficiency of the neutron tube is ~ 90%. The consequence is that the fundamental energetic advantage of the spallation source (30 MeV per neutron produced) over the D-D or D-T generator (2000 MeV per neutron for D-T) is lost.



The calculations of the neutron spectrum also allow one to determine the time structure of the neutron pulse from a neutron tube with a thin moderator. In that case we have considered an initial pulse from the tube of duration 1 μs. As the figure indicates, the moderated pulse still has a very sharp time structure (17 μs FWHM) in the case of thermal neutrons.

Another comparison of the utility of a 1 A neutron tube can be seen in the application of providing a source of neutrons for Boron Neutron Capture Therapy of glioblastoma – a cancer of the connective tissue of the central nervous system. In BNCT a tumor-seeking drug containing a large mass fraction of boron (a "neutron sponge") is administered to the patient. After a short waiting period while drug fixes in the tumor and clears from blood. At this point, the patient receives the radiation dose of roughly 30 Gray of epithermal neutrons. With the correct neutron spectrum the radiation effects will be concentrated in the cancer cells not in the healthy tissue. For a 1 amp, 80 keV tube the spectrum can be moderated to be far more favorable to therapeutic requirements than a reactor with the same ~45 minute exposure time. The neutrons outside the shaded region (i. E., less than 1 keV) will destroy healthy tissue rather than penetrate to the tumor and deliver a sufficient dose to kill the tumor. Since the actual dose must be set to spare the healthy tissue in front of the tumor reactors have led to doses insufficient to





control the tumor. In contrast a neutron tube can produce an nearly ideal spectrum leading to high tumor control probabilities even with available drugs.

In summary, the combination of efficient dc-power supplies and a new generation of plasma-based D-D neutron generators can lead to an expansion of university-based neutron science at a level which is comparable with all but the highest flux applications of reactors and spallation sources. These tubes would allow a renewal of nuclear engineering programs on university campuses and a spreading of neutron science and technology unaccompanied by nuclear proliferation concerns.

I would like to acknowledge the research efforts of Prof. Ka-ngo Leung and his group in my division at LBNL for their remarkable developments in plasma-based neutron generators. I am also grateful to Prof. Antonino Zichichi and the staff of the Ettore Majorana Center for Scientific Culture for their hospitality during this International Seminar. This work was supported by the Office of High Energy Physics of the U.S. Department of Energy under Contract No. DEAC03-76SF00098.

Table 1. Applications of Compact Neutron Sources

- ✿ Condensed Matter Physics (10^7 n/cm^2/s)
  Scattering of slow neutrons in condensed matter (solids or liquids) can determine structure on the atomic or molecular level. Neutrons penetrate deeply into matter enabling study of new materials in real T, P, and other ambient conditions
- ✿ Material Science (10^7 n/cm^2/s)
  Study point defects, dislocations, inter-phase boundaries, intrinsic junctions with micro-cracks, pores, etc.
- ✿ Molecular Compounds (10^7 n/cm^2/s)
  Small-angle neutron scattering (SANS) is a powerful method to investigate polymer systems and surface-active substances (SAS). Specular reflection provides information about the structure along the surface of the material.
- ✿ Biology (10^7 n/cm^2/s)
  Neutrons can "see" hydrogen better than photons, which enables determining details of the structure and function of biological systems
- ✿ Engineering Analysis (10^6 - 10^7 n/cm^2/s)
  Neutron diffraction probes internal stresses deep in multiphase materials
- ✿ Earth Sciences (10^6 - 10^7 n/cm^2/s)
  Neutrons probe study the texture of rock materials and minerals and effects of the external pressure on the structure of samples
- ✿ Medicine (10^9 n/cm^2/s)
  Neutron capture therapy
- ✿ "Forensics" (10^6 - 10^7 n/cm^2/s)
  Identify concealed materials